APPLICATION FOR UNITED STATES PATENT

NON-DESTRUCTIVE METHOD OF PREDICTING PERFORMANCE OF CERAMIC COMPONENTS

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NON-DESTRUCTIVE METHOD OF PREDICTING PERFORMANCE OF CERAMIC COMPONENTS

FIELD OF THE INVENTION

This invention relates to a method of predicting the useful life of an yttria-stabilized zirconia structure when implanted in living tissue.

BACKGROUND OF THE INVENTION

A widely employed bioceramic is alumina, which is classed as bioinert. The search for an ideal bioceramic has included alumina, hydroxyapatite, calcium phosphate, and other ceramics. The first use of aluminas for implants in orthopedics and dentistry was in the 1960's and they were employed in hip prostheses as early as 1970. Since those early days the quality and performance of aluminas have improved and high-purity, high-density, fine-grained aluminas are currently used for a wide range of medical applications, e.g. dental implants, middle ear implants, and hip or knee prostheses.

Although the aluminas currently available perform satisfactorily, a further improvement in strength and toughness would increase the safety factor and may extend usage to higher stressed components. A proposed candidate to add to this list is stabilized-zirconia because of its potential advantage over alumina of a lower Young's modulus, higher strength, and higher fracture toughness. Another advantage of stabilized-zirconia is low-wear residue and low coefficient of friction. Zirconia undergoes a destructive phase change on cooling at about 1000°C from tetragonal to monoclinic, which necessitates phase stabilization by calcia, magnesia, hafnia, ceria, or yttria.

Yttria tetragonal zirconium oxide polycrystal (Y-TZP) ceramic, commonly known as Y-TZP, which typically contains three mole percent yttria, coupled with the small size of the particles, results in the metastable tetragonal state at room

temperature. Under the action of a stress field in the vicinity of a crack, the metastable particles transform, with a 3% to 4% volume increase, by a shear-type reaction, to the monoclinic phase. Crack propagation is retarded by the transforming particles at the crack tip and by the compressive back stress on the crack walls behind the tip, due to volume expansion associated with transformation to the monoclinic phase.

The well-known transformation toughening mechanism is operative in zirconia ceramics whose composition and production are optimized such that most of the grains have the tetragonal crystal structure. Y-TZP ceramics mechanical properties in air at room temperature are superior to those of zirconia-toughened aluminas and to other classes of zirconias. To the knowledge of the inventors, the biocompatibility of Y-TZPs has not been fully assessed. However, the biocompatibility of the Y-TZP has been at least preliminarily investigated.

For example, in one study by Thompson and Rawlings [see I. Thompson and R.D. Rawlings, "Mechanical Behavior of Zirconia and Zirconia-Toughened Alumina in a Simulated Body Environment," Biomaterials, 11 [7] 505-08 (1990).], it was concluded that TZP demonstrated a significant strength decrement when aged for long periods in Ringer's solution and was therefore unsuitable as implant material.

Drummond [see J.L. Drummond, J. Amer. Ceram. Soc., 72 [4] 675-76 (1989).] reported that yttria-stabilized zirconia demonstrated low-temperature degradation at 37°C with a significant decrement in strength in as short as period as 140 to 302 days in deionized water, saline, or Ringer's solution. He also reports on similar observation by others, where yttria-doped zirconia demonstrated a strength decrement in water vapor, room temperature water, Ringer's solution, hot water, boiling water, and post-*in vivo* aging.

Y-TZP components suffer a decrement in strength properties after short-term exposure to wet or humid environments. This degradation of mechanical properties occurs when moisture is present in any form, for example, as humidity or as a soaking solution for the Y-TZP component. Y-TZP components have

been observed to spontaneously fall apart after times as short as a few weeks in room temperature water. This is of particular importance in living-tissue implanted devices that contain components made of this class of material. Successful long-term implantation of devices that contain yttria-stabilized zirconia components is not feasible unless performance prediction techniques are applied to verify acceptable long term device performance.

There is a need to predict the performance of components made of Y-TZP that are intended for long-term critical applications, such as implants in living-tissue.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 presents the microstimulator.

FIG. 2 presents the ceramic processing steps to form the material.

FIG. 3 presents ceramic tube exposure data.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

A broadly applicable method of qualifying ceramic components for implantation in living tissue has been developed. It has been demonstrated that the phase transformation rate of tetragonal to monoclinic in high-purity dense yttria tetragonal zirconium oxide polycrystal (Y-TZP) is a predictor of component life.

A novel ceramic to metal brazed case has been designed for implantable microstimulators, such as the microstimulator of Advanced Bionics Corporation, 12740 San Fernando Road, Sylmar, California. U.S. Patents No. 5,193,540 and 5,324,316 present developments related to this microstimulator and are incorporated in their entirety by reference herein. Y-TZP has been selected as the ceramic material because of its high strength, favorable fracture toughness, and biocompatibility. It provides a hermetic and robust housing for the electronic module located inside. The qualification method is equally applicable to other components, such as ceramic hip implants.

The strength decrement in a humid environment varies among Y-TZP ceramics, depending upon the quality of the ceramic and its composition. This variability is related to the differences in equilibrium of microstructural parameters such as: concentration and distribution of phase stabilizer, grain size, flaw population and distribution, residual stress, density, etc.

A preferred microstimulator 2 is presented in **FIG. 1**, wherein a hollow ceramic tube 4 is preferably attached by brazing to an electrode 6 on either end of the microstimulator 2, thereby forming a hermetically sealed hollow enclosure suitable to contain electronics for either sensing or stimulating living tissue into which the microstimulator 2 may be implanted. The size of the hollow microstimulator 2 is preferably approximately 10 mm or less in diameter and 100 mm or less in length, preferably less than 6 mm in diameter with a wall thickness less than 2 mm, having a longitudinal shape capable of implantation in the immediate vicinity of selected areas of the body by expulsion through a hypodermic needle or other implantation device.

The ceramic tube 4 is comprised of a strong, hermetic material that is biocompatible, such as Y-TZP. In alternative embodiments, other stabilizer materials may be utilized in place of yttria, such as ceria, magnesia, calcia, hafnia, or other known stabilizing additives.

The Y-TZP ceramic tube 4 is formed by conventional ceramic forming processes, preferably including pressing and sintering, as shown in the respective blocks 22 and 24 of **FIG. 2**. The method of forming the tube includes raw material preparation 20, which includes particle size control and binder selection and introduction, as well as selecting the stabilizer. Post-sintering, the dense ceramic is optionally machined as shown in block 26 to final dimensions and to the required surface finish. The ceramic tube 4 is optionally further processed by hot isostatic pressing (HIPping) as shown in block 28 or other known densification methods.

The ceramic article is preferably exposed to 127°C steam, although in an alternative embodiment, the ceramic could be exposed to superheated water to achieve the same result. X-ray diffraction is used to measure the monoclinic phase content by surface examination before and after the article is exposed to the steam milieu. The monoclinic volume fraction is calculated from the modified Garvie-Nicholson equation, as described herein.

As part of the ceramic article acceptance procedure, the article is soaked in 127°C steam for a predetermined time, preferably six hours. The absolute difference in monoclinic phase content is calculated by subtracting the post-exposure monoclinic phase content, expressed in percent, from the initial monoclinic phase content, expressed in percent. If the absolute value of the monoclinic phase content difference has increased by less than 2.1%, then the article is accepted.

It has been demonstrated, **FIG. 3**, that a 2.1% increase or greater in volume fraction of monoclinic phase in an otherwise qualifying ceramic of Y-TZP, correlates well with premature failure of the ceramic after exposure to aging in a humid environment. Aging experiments conducted in 127°C steam yielded monoclinic transformation rates, R, represented by the expression

$R = Q^{((T2-T1)/10)} = 2^{((127-37)/10)} = 2^9 = 512$, where Q is an empirically derived constant, T_2 is the qualification temperature, and T_1 is the long-term use temperature, preferably body temperature. Q has been found to be equal to 2, as derived by plotting the monoclinic phase content as a function of exposure time at 127°C in steam. That is, the rate of conversion between the qualification test exposure of 127°C and that experienced at body temperature of 37°C is a factor of 512, with conversion being 512 times faster at the qualification test. [see G. Jiang, K.E. Fey, and J. Schulman, *In-Vitro* and *In-Vivo* Aging Tests of BION® Micro-stimulator, presented at the 54th Pac Coast Regional & Basic Sci Div Meeting of the Am. Ceram. Soc., Seattle, WA, Oct. 1-4, 2002.]

As presented in **FIG. 3**, the Y-TZP components that are exposed to 127°C steam spall and flake before they spontaneously degrade into powder, in some cases. The measured times are presented along with projected times to spalling and flaking at 37°C and with projected times to spontaneous destruction at 37°C. In lieu of measured volume fraction conversion after six hours exposure to 127°C, a calculated estimated monoclinic conversion is presented that is based on the mean conversion rate expressed in percent. For example, the M (2mm diameter) ceramic has a projected life in a moist environment at body temperature of greater than 80 years based on the 0.3% 6 hour conversion. By way of further example, the C (2mm diameter) ceramic has a projected life of 10.0 years when exposed to a humid environment at body temperature. This sample is rejected based on the 6-hour conversion rate of 5.3%. The inventor has arbitrarily selected 80 years as the minimum projected life to spontaneous destruction at body temperature. It is obvious that one can select a different life expectancy and therefore establish a different short-term exposure as the acceptance test level.

In an alternate embodiment, the ceramic components are initially examined and subjected to a series of screening tests, per ASTM F 1873-98, before they are subjected to the steam exposure. Only those components that pass all tests are exposed to further qualification testing.

For ceramic components having a geometry that makes it difficult to test the corresponding mechanical properties directly, a "witness" sample may be substituted, where the witness sample has been processed in an identical series of process steps as the component itself.

The chemical composition of the ceramic component is measured by X-ray fluorescence (XRF) or mass spectroscopy to be greater than or equal to 99 weight percent ZrO2 HfO_2+ Y_2O_3; 4.5 to 5.4% Y_2O_3; less than 5% HfO_2; less than or equal to 0.5% Al_2O_3; and less than or equal to 0.5% of other total oxides.

The minimum bulk density of the ceramic component is greater than or equal to 6.00 g/cm^3. The total porosity is less than or equal to 1.0 volume percent and open porosity is no greater than 0.1 volume percent. Grain size is less than or equal to 0.6 microns as measured by the mean linear intercept distance.

The initial monoclinic phase content is 5 percent or less on a polished surface with surface finish equivalent to 0.05 microns. The peak height of the tetragonal phase, T(111) at $2\theta = 30.2°$, and monoclinic phase, $M(\bar{1}11)$ at $2\theta = 28.2°$ and M(111) at $2\theta = 31.3°$ is identified by X-ray diffraction (copper K-alpha radiation) analysis to calculate the percent of monoclinic phase by the equation:

monoclinic phase content = $M(\bar{1}11) + M(111)/M(\bar{1}11) + T(111) + M(111)$.

The mean room temperature flexural strength is 800 MPa (116 Ksi) or greater by four point bending for a minimum of ten samples.

The minimum room temperature elastic modulus is 200 GPa ($29x10^6$ psi). The minimum Vickers hardness value is 1200 HV with a 1 Kg load and a 15 second dwell time. These measurements are all conducted in accord with ASTM F 1873.

An alternate embodiment of the acceptance test involves acoustic emission inspection of the accepted ceramic tubes along the longitudinal axis. If a flaw greater than 3 microns is observed, the tube is rejected.

As an additional embodiment of the acceptance test, the accepted ceramic tube may be loaded in a flexural bending mode so as to pre-load the

tube at a known stress. The stress for this proof test type of qualification is preferably 800 MPa, although higher or lower stresses may be used to either change the acceptance rate or to assure a select minimum failure strength. Because of the small size of the tube, three-point bending may be utilized to pre-load the tube, although four-point bending is preferable when the sample is sufficiently long to allow such loading. Tubes that fail to survive the pre-load are thus culled from the sample population thereby giving a minimum strength for the survivors.

Obviously, many modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood that, within the scope of the appended claims, the invention may be practiced otherwise than as specifically described.